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N. V. Krasnogorskaya

INVESTIGATION INTO THE CONDITIONS FOR UTILIZATION OF THE KUBETSKIY "MOSAIC" MULTIPLIER AS AN INDICATOR OF THE MAGNETIC FIELD *

(Submitted by Academician O. Yu. Shmidt)

The possibility of constructing an inertialess magnetometer based on the secondary electron multiplier of Kubetskiy, with magnetic focusing, is investigated. The conditions for input stability of the amplifier at a given degree of accuracy of measurement of magnetic field intensity are calculated, together with the limits of possible measurement.

A considerable number of new problems confronting geophysicists and magnetologists in practice demand the development of new ~~apparatus~~ and the perfection of old [redacted] apparatus.

The methods of measuring the magnetic field which are being worked out in the Terrestrial Magnetism Section of the Geophysical Institute, Academy of Sciences USSR, are mostly based on induction (1). They permit determination with a sufficient degree of precision, of slight variations in the magnetic field, with cycles not less than 1 to 2 seconds. The sensitivity of the apparatus drops sharply for shorter impulses.

* [Note: Figures are in the appendix.]

Geophysicists, however, are interested in the study of a whole series of processes, rapidly proceeding in time, of variation in the magnetic field. Such processes may originate in ionospheric phenomena (magnetic storms, for example) or in processes taking place in the hard outer shell of the earth's crust.

The preliminary investigations by A. G. Kalashnikov into the relation between various geophysical phenomena and the variations in the magnetic field showed frequency and shape of the impulse to be of great significance for the study of this relation. In particular, the magnetic effect of meteorites may be revealed by the characteristic "peaks" on the magnetograms.(2).

In connection with this the necessity for extending the frequency-range of magnetic-field measurements arises, so as to make it possible to register more precisely the shape of the impulse and to detect the more rapid shocks, which escape measurement by the inductive method.

At the present time, high-sensitivity magnetometers (3), based on the non-linear magnetic characteristics of iron-nickel alloys, are being extensively developed; and these probably could be employed in the solution of the instant problem.

We commenced to seek a solution in the utilization of electronic devices with steep magnetic characteristic curves.

Two types of such devices are well-known: the magnetron, a special type of diode, and the secondary electron multiplier of Kubetskiy (4) with magnetic focusing.

The application of the magnetron to magnetic measurement has been studied by many investigators, both in laboratories (5) and under field conditions (6). In spite of a number of points in which the magnetron is superior to other magnetometers used in practice, it has not been very generally accepted for this purpose, principally because of the insufficient stability of the anode current, due to the relatively large constant component and the mechanical vibration of the incandescent filament.

We investigated the possibility of constructing an inertialess magnetometer, using another electronic device possessing a steep magnetic characteristic curve: the secondary electron multiplier (tube) of Kubetskiy (7).

It is obvious that in using a photomultiplier as an indicator of magnetic field strength, it is not the absolute value of the anode current which plays the essential role but the magnitude of its increase under the influence of variation in magnetic intensity. The effect of the action of the magnetic field on the anode current of the amplifier will be more pronounced, the more sharply the focusing conditions of the electron beam change with the variation of magnetic field strength.

The construction of such a photomultiplier designed to intensify the increase of the anode current that occurs under the influence of external magnetic action, was proposed by L. A. Kubetskiy. This amplifier received the designation of Kubetskiy "magnetic" tube with mosaic emitter, or for short, simply "mosaic" photomultiplier.

The mosaic photomultiplier, of which a general view is shown

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in Figure 1, has a copper-sulphur-caesium photocathode and six cascade stages of amplification. Each dynode of the mosaic photomultiplier consists of two emitting layers: a copper-sulphur-caesium layer, active with respect to the secondary emission, and an inactive silver layer. The alternation of the dark copper-sulphur-caesium with the light silver layers gives it the "mosaic" appearance responsible for its name.

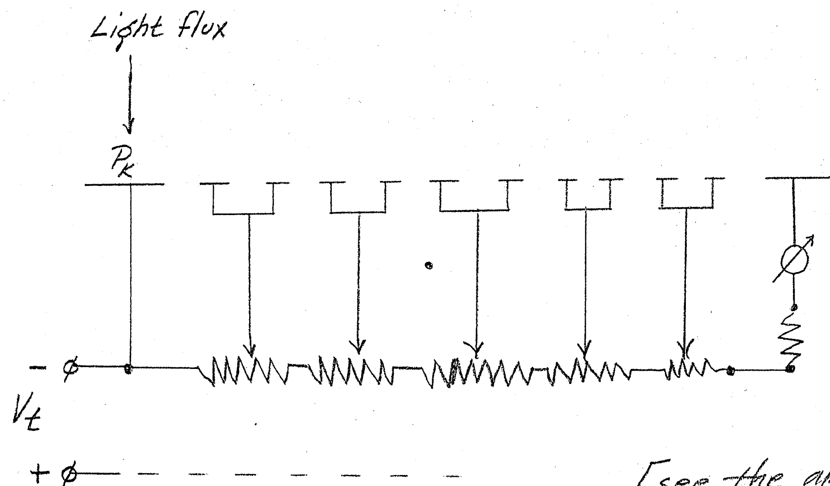
The primary beam of electrons ejected by the cathode is subjected to the action of the interlacing electric and magnetic fields, which give the electrons a definite trajectory. When an additional external magnetic field is superimposed upon the photomultiplier, functioning under a definite regime, the electron beam is shifted from a sensitive emitter to an insensitive one (or the reverse) and the anode current falls more sharply than could have occurred in the ordinary electron photomultiplier. By measuring the variation in anode current, the magnetic field acting on the instrument may be determined.

CONDITIONS AND METHODOLOGY OF THE EXPERIMENT

Figure 2 shows the electrical measurement circuit. The full anode current is measured by a needle galvanometer with a sensitivity of the order of 10^{-6} (Amperes per division.) ~~del/A.~~ The increase in the anode current under the influence of an external magnetic field is measured by the compensation method with the aid of a mirror-galvanometer with a sensitivity of the order of 10^{-8} to 10^{-10} A./divn. ~~del/A.~~

In view of the fact that the operational stability of the amplifier essentially depends on the constancy of the luminous flux, we used a compensating scheme for the incandescent filament which made it possible to control the constancy of the current within the limits of $\pm 0.7 \times 10^{-6}$ A.

The supply of voltage to the photomultiplier, which was furnished by dry cells, varied from 300 to 1000 volts.



[see the appendix]

Figure 2. Electric Circuit Including the Mosaic Photomultiplier. P_k - Photo-cathode; A - Anode of photomultiplier; I - VI - Dynodes of the photomultiplier; (Cu - Copper-sulphur-caesium layer; Ag - Silver layer); G - Needle-galvanometer; - G_o - Mirror-galvanometer

The magnetic focusing systems we used were of two types: systems producing a negative gradient of the magnetic field in the operating regions of the photomultiplier (in which case the magnetic system is disposed beneath the instrument, as is usually the case with the ordinary Kubetskiy photomultiplier), and magnetic systems creating an almost uniform field in the operating portions of the photomultiplier.

To evaluate the sensitivity of the photomultiplier to an external magnetic field, we applied the method of superposition of a supplemental uniform magnetic field upon the magnetic field belonging to the instrument itself. The intensity of the supplemental field could be calculated with a sufficient degree of accuracy. For this purpose we used a Helmholtz ring of suitable dimensions.

The basic measurements were made by the following methodology:

1. We took the magnetic characteristics of the photomultiplier with a given magnetic system (i.e. the dependence of the anode current on the intensity of the internal magnetic field).

2. According to the magnetic characteristic obtained, a working point was selected in its steep part.

3. Setting up the operating conditions of the photomultiplier corresponding to the working point selected, we compensated the constant component of the anode current and then measured the rise in that current when a uniform external magnetic field, produced by a Helmholtz ring, was imposed upon the instrument.

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4. In this way we obtained a dependence of the growth of the anode current upon the intensity of the external magnetic field;and from this dependence we calculated the sensitivity of the amplifier to a uniform external magnetic field (the magnetic sensitivity) under given operating conditions.

During these measurements the vectors of the external and internal magnetic fields were collinear.

RESULTS OF THE EXPERIMENT

The anode current of the photomultiplier is a function of a number of parameters.

For an amplifier of a given construction the anode current i_a is a function of the total input voltage V_t, the light flux Φ and the intensity H of the magnetic field:

$$i_a = f\,(V_t, \Phi, H).$$

The expression for the intensity of the full vector of the magnetic field is composed of two components:

$$\overline{H} = \overline{H}_o + \Delta\,\overline{H}$$

where $\overline{H}_o$ is the internal magnetic field (belonging to the instrument itself) and $\Delta\,\overline{H}_o$ is the external magnetic field to be measured.

To determine the optimum operating conditions of the instrument as an indicator of the magnetic field, the choice of the parameters V_t, Φ and $\overline{H}_o$ must be made with a view to obtaining the maximum sensitivity of the instrument to all changes in the magnetic field, and also to obtaining adequate stability of the anode current.

In other words, the optimum operating conditions of a secondary electron multiplier, as an indicator of the magnetic field, will be those conditions under which the derivative di_a/dH is greatest and the derivatives di_a/dV_t and $di_a/d\Phi$ are smallest.

In our search for these optimum operating conditions we obtained the magnetic characteristics for various magnetic focusing systems.

Based on a large number of experimental data we reached the conclusion that the magnetic characteristics of the photomultiplier maintain a very clearly expressed maximum for all variants of magnetic focusing systems tried by us, with the maximum steepness of the magnetic characteristic di_a/dH assuring a uniform internal magnetic field.

Figure 3 shows the magnetic characteristics for various input voltages to the photomultiplier operating with a uniform internal magnetic field.

By selecting our working points on the steep part of the magnetic characteristics presented and imposing an external magnetic field on the photomultiplier, operating under corresponding conditions, we obtained the characteristics shown in Figure 4 for the dependence of the rise in anode current on the intensity of the external uniform magnetic field.

It follows from the graphs in Figure 4 that when the input voltage is reduced (in this case to 160 volts) the magnetic sensitivity of the photomultiplier falls (in this case to one-sixth). The reduction of the influence of the magnetic field on the anode current as the input voltage falls is due to the reduction of the coefficient of secondary emission σ , which, as is well-known, is a function of the velocity of the electrons (8).

It follows from the graphs in Figure 5 that the magnetic sensitivity increases with intensification of the luminous flux (on account of the increasing number of electrons participating in the secondary electron multiplication.)

The value of the luminous flux which would be optimal for the functioning of the amplifier as an indicator of the magnetic field is limited, however, by the normal operating conditions of the photocathode.

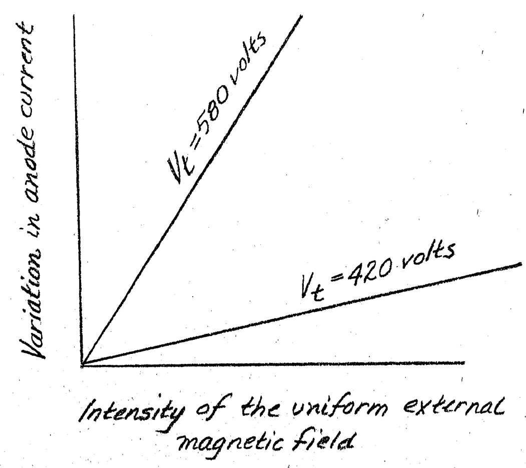

Figure 4. Dependence of the Rise in Anode Current on the Uniform External Magnetic Field. ▽ represent the control points.

Figure 5. Dependence of the Magnetic Sensitivity on the Luminous Flux. ⊙ -- Vector of the internal magnetic field opposed to the external field ($H_o \uparrow \downarrow H_{BH}$). △ -- Vector of the internal magnetic field coinciding in direction with the external field ($H_o \uparrow \uparrow H_{BH}$).

THE CONDITIONS FOR STABILITY OF INPUT AT A GIVEN ACCURACY OF MEASUREMENT ΔH

We calculated the conditions for stability of input to a photomultiplier, the fulfillment of which conditions would be sufficient to assure the uninterrupted measurement, with a given degree of accuracy, of the rise in the intensity of an external magnetic field (9).

To make it possible to measure the increase ΔH in the external magnetic field, with the accuracy δH, the values of the fluctuation Δi_H in the filament current, of the fluctuation ΔV_t in the total input voltage, and of the fluctuation ΔH_o in the internal magnetic field, must satisfy the following inequalities:

$$\Delta i_H \leqslant \frac{1}{3} \frac{\partial i_a}{\partial H} \frac{\partial i_H}{\partial i_a} \delta H,$$

$$\Delta V_t \leqslant \frac{1}{3} \frac{\partial i_a}{\partial H} \frac{\partial V_t}{\partial i_a} \delta H,$$

$$\Delta H_o \leqslant \frac{1}{3} \frac{\partial i_a}{\partial H} \frac{\partial H_o}{\partial i_a} \delta H.$$

Substituting the value of the magnetic sensitivity with a uniform internal magnetic field -- $\gamma_H = \frac{\partial i_a}{\partial H} = 14 \times 10^{-6}$ A/oerstad -- and the values of the partial derivatives obtained from experimental data, we arrive at the following conditions for stable input in measuring the intensity of an external magnetic field by the photomultiplier, for instance, with the accuracy of measurement

$$\Delta i_H \leqslant 0.9 \times 10^{-5} \text{ A}, \qquad (1)$$

$$\Delta V_t \leqslant 0.7 \times 10^{-2} \text{ volts} \qquad (2)$$

$$\Delta H_o \leqslant 0.3 \times 10^{-3} \text{ oerstad} \qquad (3)$$

The fulfillment of the condition requiring constant intensity of the internal magnetic field of permanent magnets depends on the whole on temperature conditions. If we admit that the variation in the magnetic moment of permanent magnets is proportional to the variation in the intensity of the magnetic field in the operating area, then, if condition (3) is to be fulfilled, the variation in the temperature of the permanent magnets should not exceed 0.1°.

[$V_{об} = V_t$; эрст = oerstad; в = volts]

Figure 6. Family of Magnetic Characteristic Curves of the Amplifier, with a Uniform Internal Magnetic Field.

[$V_{об} = V_t$; эрст = oerstad; в = volts]

Figure 7. Family of Ampere-Volt Curves with a Uniform Internal Magnetic Field.

It must be observed that the above-described conditions for stable input to the photomultiplier can be considerably relaxed, either by increasing the steepness of the magnetic characteristic (by making the necessary improvements in the construction of the instrument) or, using the given tube, by setting up special operating conditions for it.

The latter method may be illustrated by the choice of the total input voltage. It follows from the family of magnetic characteristic curves presented in Figure 6 that, with respect to the value of the magnetic sensitivity of the photomultiplier, the working points on the right and left branches of the magnetic characteristics are equivalent. With respect to stability of operation, however, the choice of a working point on the left side of the magnetic characteristic (with a lower value for the intensity of the internal magnetic field) is as a rule more advantageous than on the right side. For instance, with an input voltage V_t = 500 volts, a working point situated on the left branch of the magnetic characteristic and having the coordinates i_a = 35 μA, H_o = 39 oerstads will fall on the flat part of the ampere-volt curve (with an internal magnetic field H_o = 39 oerstad), where the anode current varies only insignificantly with the input voltage; while the working point situated on the right branch of the same magnetic characteristic, with the coordinates i_a = 35 μA, H_o = 43 oerstads, will fall on the steep part of the corresponding ampere-volt curve (with H_o = 43 oerstads) where the anode current varies much more sharply with the input voltage (see Figure 7).

THE LIMITS OF MEASUREMENT

The lower limit of possible measurement or the threshold of magnetic sensitivity of the instrument, i.e. the lowest value of the intensity of magnetic field that can be measured by this amplifier, is fixed by the electrical fluctuations of the anode current.

The electrical fluctuations of the photomultiplier consist on the whole of thermal-agitation noise in the output resistance and of noise from the shot-effect. We calculated the ratio of the squares of the thermal and shot effects -- $\frac{V_{th}^2}{V_{sh}^2}$ -- to be far less than unity in the case of the given amplifier:

$$\frac{V_{th}^2}{V_{sh}^2} = 13 \times 10^{-6} \ll 1$$

Consequently, thermal-agitation noise in the photomultiplier circuit may be disregarded. The amplitude of the noise current due to the shot-effect was calculated by us to have the following value under optimum operating conditions of the photomultiplier, when used as an indicator of magnetic field strength:

$$\sqrt{\bar{j}^2} = 1.4 \times 10^{-10} \sqrt{f} \text{ A.}$$

The band of frequencies f passed by the instrument is limited by the measuring device connected to the output of the photomultiplier. If, for instance, the rise in anode current is measured by a galvanometer with a period of 1 second, the amplitude of the noise current will be

$$\sqrt{\overline{j^2}} = 1.4 \times 10^{-10} \text{ A.}$$

If we assume that it is sufficient for measurement to have the signal to be measured three times as great as the noise, then the lower limit of possible measurement for a photomultiplier with a magnetic sensitivity $\gamma_H = 14 \times 10^{-6}$ A/oerstad will be

$$\Delta H_{thr} = 3\,\frac{14 \times 10^{-11}}{14 \times 10^{-6}} = 3 \times 10^{-5} \text{ oerstad.}$$

The upper limit of possible measurement is determined by the length of the projection of the linear part of the magnetic characteristic curve upon the axis of abscissas. This upper limit of possible measurement of variations in magnetic field strength for the photomultiplier studied by us, is ± 1.3 oerstad, on condition that the working point is selected in the middle of the steep part of the magnetic characteristic.

In conclusion I express my profound gratitude to the director of this work, A. G. Kalashnikov, active member of the APN, for a number of valuable instructions.

Academy of Sciences USSR
Geophysical Institute

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APPENDIX

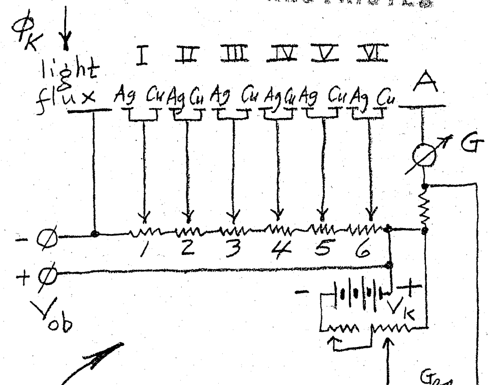

Figure 2. Electric circuit showing the connection of the mosaic photomultiplier.

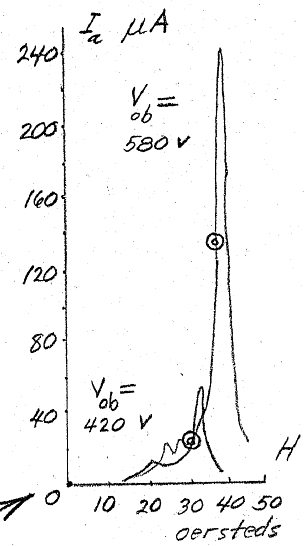

Figure 3. Magnetic characteristics of the mosaic multiplier. ⊙ - operating points.

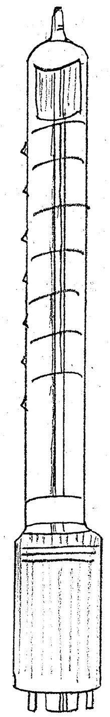

Figure 1. Mosaic multiplier.

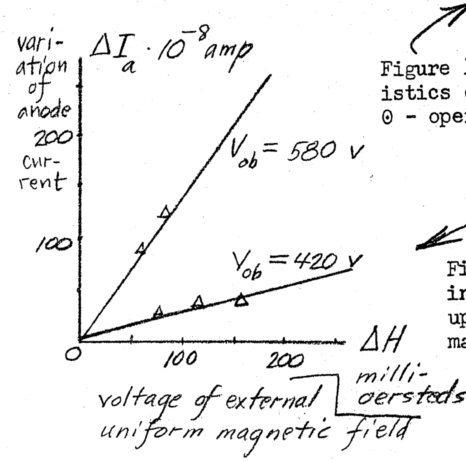

Figure 4. Dependence of increment of anode current upon external uniform magnetic field. ∇ - control points.

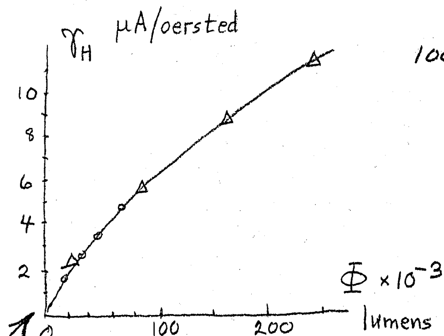

Figure 5. Dependence of magnetic sensitivity upon light flux. ⊙ - vector of natural magnetic field is opposite to the external field ($H_o \uparrow\downarrow H_{ex}$. Δ - vector coincides ($H_o \uparrow\uparrow H_{ex}$).

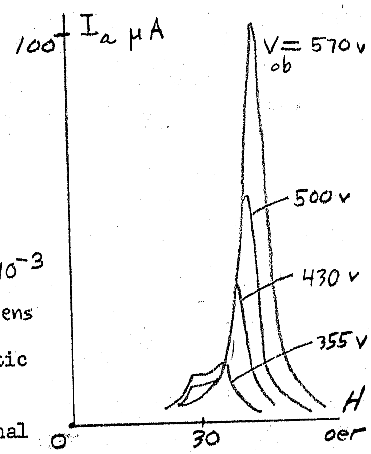

Figure 6. Family of magnetic characteristics of multiplier for uniform natural m magnetic field.

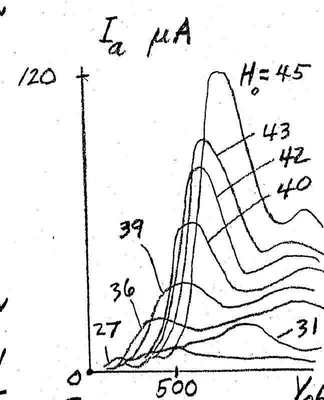

Figure 7. Family of volt-ampere characteristics for uniform natural magnetic field.

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